Characterization, Rheological and Pipe Loop Test Studies on Fly Ash Samples

In partial fulfilment of the requirement for the degree

of

Master of Technology

in

Thermal Engineering Specialization

by

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Under the guidance of

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CERTIFICATE

This is to certify that the report entitled **"CHARACTERIZATION, RHEOLOGICAL AND PIPE LOOP TEST STUDIES ON FLY ASH SAMPLES"** submitted to the National Institute of Technology, Rourkela by **Rashmiranjan Barik**, Roll No. **211ME3356** in partial fulfillment of the requirement for the degree of **Master of Technology** in **Department of Mechanical Engineering** with specialization in **Thermal Engineering** is a record of bona fide work carried out by him under my supervision and guidance.

Place: NIT Rourkela, **Date:** 2nd June 2014

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Date: 2nd June 2014 Signature

Contents

List of Symbols and Abbreviations

Symbol	Description
μ	Viscosity of the slurry (Kg/m-s)
$C_{w\text{-}max}$	Maximum static settled concentration(%)
τ	Shear stress(pa)
n	Flow behaviour index
K	Consistency index
γ	Shear rate(sec^{-1})
W_s	Solid flow rate(tonnes/hr)
Q	Slurry flow rate(m^3/hr)
ρ_m	Slurry density(tonnes/m^3)
C_w	Weight concentration of solids(fraction)
D	Pipe inside diameter(m)
P_H	Hydraulic power(kw)
ΔH	Head loss of slurry(m of water per km)

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Abstract

In India, about 75% of total electrical energy is generated from thermal power plants which in turn release about 130 million tones of fly ash is a major problem faced by the power plants. Presently fly ash is being transported as lean slurry in pipe lines requiring about 80 to 85% of water with more energy input. The objective of the present study was to evaluate fly ash characterization-mainly particle size distribution, material; density, sedimentation tests(maximum static settled concentration), rheological analysis for measuring viscosity, and pipe loop tests studies in 50 mm and 100 mm diameter pipes for the 130 MW and 100 MW power plant ash samples generated at BPSL integrated steel plant, Rengali, Sambalpur. The sedimentation (maximum static settled concentration) tests conducted on the two ash samples for the proposed HCSD systems (Pumping Station-1 and Pumping Station-2) indicated that the mixed ash sample for the Pumping Station-1 can be transported at a higher solids concentration than that of Pumping Station-2.The maximum static settled concentration (Cw-max) value of pumping station 1 and 2 were determined to be 68.18% and 68.8% respectively. The rheological analysis of the proposed pumping station-1 ash samples indicated higher viscosity than pumping station-2 in the slurry concentration range of 50-65% by weight. The pipe loop tests conducted in 50 mm and 100 mm diameter pipes using the two ash samples indicated that it is quite feasible to transport the ash slurry at higher solids concentration in order to save energy and precious water substantially.

Keywords: *Rheology, Fly ash, Shear stress, viscosity. Shear rate*

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

In India the only natural resource is coal and fossil fuel available in plentiful. Accordingly it is used widely as a thermal energy source and also as fuel of producing electricity for thermal power plants. Currently 86015 MW of thermal generation (as on march 2007) has installed in India constituting 65% of total installed capacity. With the blast of population and industrial growth, the requirement for power has altered manifold. Almost 73% of India's total installed power generation capacity is thermal, of which 90% is coal-based generation, with diesel, wind, gas and steam making up the rest. To fulfill the projected demand in 2011-12, the requirement of additional capacity of about 7,800 MW is demanded in 11^{th} plan (2007-2012). Thermal power generation is anticipated to continue to play a major role in power generation sector. The main problem in using coal is low calorific value and contains very high ash. The ash content is as high as 55-60%, with an average value of about 35-40%. Huge amount of coal ash produced due to low calorific value and ash content up to 40% of Indian coals of 5-6 tonnes per MW per day. Alternatively, many power stations in developed countries create far lower quantum of ash, about 0.6-0.7 tonnes per MW per day due to high calorific value and lower ash content around 10% in their coals.

Fly ash is generated in huge quantities in thermal power stations and constitutes about 80% of the total ash produced. The rest 20% of the ash is in granular form and poses no threat to the environment or any disposal problems. The fly ash being of the fine size is environment pollutants and need to be transported with utmost care so that they don't cause any hazard to the ambience. This is generally done in the ash handling plant employing electrostatic precipitators and transported to places of its utilization using hydraulic transportation through pipelines. This process has been accepted as an economic and efficient method of transportation of fly ash also. A majority of power plants in our country have installed short pipelines for the transportation of fly ash to the disposal ponds. Unfortunately this transportation is being done at low concentrations of solids, generally in the range of 10-20% by weight. This is extremely uneconomical as it results in the high requirement of carrier water and high operational cost since the power consumption for transporting until weight of fly ash through unit distance. Besides, this high concentration fly ash slurry can be effectively used for back filling the coal mine cavities. Hence the hazard posed by fly ash can be controlled to a great extent. The present investigation aims at establishing the feasibility of a fly ash slurry handling system with pipeline transportation of fly ash slurry at higher concentrations in order to provide an Eco-friendly, economical and effective process of fly ash disposal.

1.2 Scope of the project

- Fly ash characterization – mainly Particle size Distribution
- Determination of density & specific gravity of the ash samples
- Sedimentation Test (Maximum static settled concentration studies) of ash samples for the proposed two HCSD systems.
- Rheological Analysis for measuring viscosity of the ash samples
- Pipe loop tests studies

1.3 Objective of the project

- Characterization, rheological and pipe loop tests of 02 different ash samples i.e from 130 MW and 100 MW Silo at BPSL integrated steel plant, Rengali, Sambalpur.

1.4 Literature review

A number of studies on rheological and pipe flow behaviour of coal ash slurry at low to medium concentration (Cw=10-50% by weight) have been described in literature (Iwanami & Tachibana (1970), Wright & Brown (1979), Verkerk (1982), IMMT's Internal report, 1987; Parida et al., 1988, Verkerk (1985) and Verkerk et al. (1993), Lazarus and Sive (1984), Vlasak et al. (1993).

The hydraulic transportation of fly ash –bottom ash mixture slurry at high concentration is very insufficient in literature. Verkerk (1982) has performed some very useful investigations on the hydraulic transportation of fly ash of South African power stations. A 100 m long pipeline-test loop with a pipe dia of 100mm was used with a reciprocating piston pump for high concentration pastes of 65 to 70% by weight. The slurry head loss results acquired by Verkerk from the loop tests were consistent with the typical homogeneous slurry characteristic curves. A kink in the curve was detected when the head loss data plotted in logarithmic scale at a flow rate of about 20-25 m3/hr which corresponded to the visual observation of the unset of deposition on the bottom of the pipeline. Tests at high concentrations showed presence of a yield stress which was due to the non-Newtonian behaviour of the slurry. The slurry changed from fluid like character to one that inclined form sliding planes at 68-69% weight concentration. The pumping of high concentration paste above 69% concentration obtained high pressure loss. However it was noticed that a paste having a fraction of bottom ash incurred substantially less pressure drop. But Streat (1986) in his paper has raised the certain questions on the decrease in pressure drop in presence of coarse particles, terming the phenomenon as surprising and needing explanation.

Bunn et al. (1990, 1991) have initiated a number of studies on high concentration slurries of fly ash from some of the Australian power stations. The fly ash slurries were found to be time independent and exposed non-Newtonian behaviour for solids concentration which is greater 60%. For solids concentrations close to 60%, a Bingham model closely fitted the measured curve. At high concentrations, the rheology curve deviated from Bingham plastic model. At high strain rates, the agreement between the data and Bingham model was good but below a critical shear rate, pseudo-plastic exponential model closely fitted the measured data. Studies on the dense phase hydraulic conveying of fly ash at Vales Point power station in Australia have been reported by some authors (Bunn, 1989; Bunn et al., 1993). It was showed that the optimum concentration of slurry in the pipeline would be around 60% by weight.

Heywood et al. (1993) examined the flow characteristics of pulverized fuel ash slurries at high concentration in the range of 68 to 70% weight concentration, the d50 of the sample being 38 microns. The authors established pressure loss-flow rate relationship by conducting experiments in a 72 mm ID, 8.34m long polypropylene plastic pipe. A power law model was fitted to the lower shear rate range data appropriate for prediction of frictional losses in 150mm and 200mm dia pipelines over a distance of 8 km. The power law exponent ‘n’ was found to be largely constant at around 0.46 for two types of pulverized fuel ash probed.

Singh et al. (1998) probed the rheological properties of fly ash-water slurry at obtained from three different sources. The difference in the behaviour of the fly ash water slurries from different power stations was attributed to the nature of mineral matter in the coal, size distribution of the pulverized fuel and the combustion conditions in the boiler. He completed that the development of high concentration slurry disposal system is very much dependent on the source of fly ash.

Parida et al. (1995, 1996) explored the rheological and pipe flow behaviour of ash samples from Talcher Thermal Power Station, Orissa. The viscosity of the fly ash slurry was found to be Newtonian in nature upto a solids concentration (Cw) of 50% and above this concentration the viscosity is non-Newtonian. The power law pseudo-plastic model correctly characterizes the non-Newtonian viscosity of fly ash slurry. By using appropriate Newtonian and non-Newtonian models the head loss of the slurry were predicted. It was informed that the transportation cost of fly ash slurry reduces drastically if the same is transported at high concentrations instead of low concentrations.

Ward et al. (1999) and Hiromoto et al. (2001) probed the hydraulic transportation of dense fly ash slurry using a stabilizing additive to prevent sedimentation of fly ash particles. But the addition of stabilizing additive increased the slurry viscosity for which a dispersing additive was to be used to finalise the problem.

Biswas et al. (2000) examined on various solid properties of fly ash and bed ash collected from Indian thermal power plants. It was pointed out that the properties of different ash samples (both fly ash and bed ash) vary over a wide range. The rheological properties of the ash slurries at different concentrations display a wide variation and thus the design of ash disposal pipe line is very much dependant on the rheological parameters from optimization of energy and water consumption point of view.

CHAPTER 2

CHARACTERIZATION STUDIES ON BPSL ASH SAMPLES

2.1 Introduction

The fly ash generated from different boilers for the proposed two high concentration ash disposal systems are given below as informed by BPSL officials.

Unit 1 Pumping Station (proposed)		
Ash type	**Quantity in tph**	**Source of ash**
Bed ash	37	Will be collected from AFBC boiler 1 & 2 + CFBC boilers (2x120 tph)
Fly ash	162	Will be collected from WHRB (1 to 4) , de-dusting systems 1 & 2, CFBC (2x120 tph) and AFBC 1&2
Total ash	199	-
Unit 2 Pumping Station (proposed)		
Ash type	**Quantity in tph**	**Source of ash**
Bed ash	57	Will be collected from CFBC boiler (4x210), CFBC 390 tph and CFBC 150 tph boiler
Fly ash	513	Will be collected from CFBC boiler (4x210), CFBC 390 tph, CFBC 150tph, WHRB 5 to 14 and de-dusting system 3 to 7
Total ash	570	-

From the above tables, it is seen that for Pumping Station 1, the generation of bed ash is approximately 19% of the total ash i.e. fly ash + bed ash and the weight ratio of fly ash to bed ash is 4.4 :1. Similarly for Pumping Station 2, the generation of bed ash is 10% of the total ash i.e. fly ash + bed ash and the weight ratio fly ash to bed ash is 9:1. The proposed pumping Station 1 comprises of ash from WHRB boilers, CFBC boilers, AFBC boilers and De-dusting unit. Similarly the Pumping Station 2 comprises of ash from WHRB boilers, CFBC boilers and De-dusting unit.

2.2 Chemical Composition of ash samples

Using Philips (PANanalytical) Pw 2440 MagiXPRO wavelength- dispersive sequential type X-ray fluorescence spectrometer with Rh-target, the elemental composition of the two ash samples namely Pumping Station-1 and Pumping Station-2 were determined. The chemical composition of the two ash samples is presented in table 1 and table 2.

Table 1:Chemical analysis of Pumping Station-1 fly ash samples, BPSL, Sambalpur

Fly ash Samples	
Compound Formula	**Concentration (%)**
Na_2O	0.78
MgO	0.26
Al_2O_3	20.65
SiO_2	52.25
P_2O_5	0.18
K_2O	0.19
CaO	0.62
TiO_2	0.35
Fe_2O_3	15.28
LOI	7.46
Other Components	
	mg/Kg
S	76
As	142
Sb	14.1
Sr	110
V	95
Cu	51
Cr	33

Table 2:Chemical analysis of Pumping Station-2 fly ash samples, BPSL, Sambalpur

Fly ash Samples	
Compound Formula	**Concentration (%)**
Na_2O	0.72
MgO	0.23
Al_2O_3	28.87
SiO_2	59.5
P_2O_5	0.27
K_2O	0.12
CaO	0.59
TiO_2	0.39
Fe_2O_3	6.02
LOI	1.3
Other Components	
	mg/Kg
S	70
As	190
Sb	9.5
Sr	136
V	99
Cu	57
Cr	21

2.3Particle Size Distribution of ash samples

The particle size distribution of different ash samples supplied by M/s BPSL for the proposed high concentration ash disposal pumping stations were carried out using Malvern Particle Size Analyzer and standard BS sieves. The particle size distribution of all the ash samples are given in Tables 3 to 13 and are plotted in Figures 1 to 11.

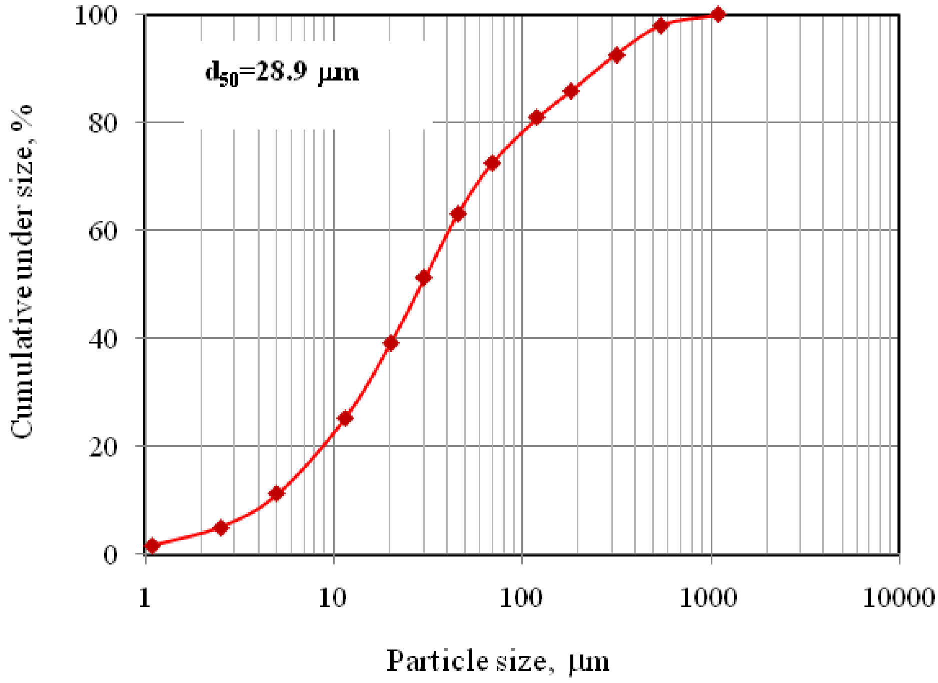

Fig.1: Particle Size Distribution of ash samples (Proposed HCSD Pumping Station-1) (Bhushan Power & Steel Ltd., Rengali, Sambalpur)

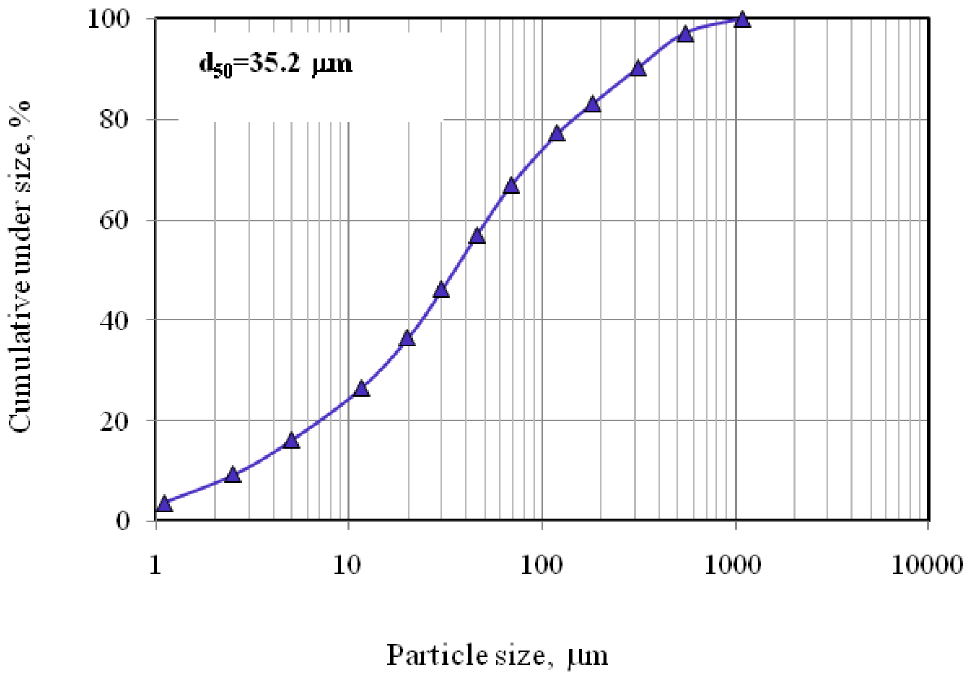

Fig.2: Particle Size Distribution of ash samples (Proposed HCSD Pumping Station-2) (Bhushan Power & Steel Ltd., Rengali, Sambalpur)

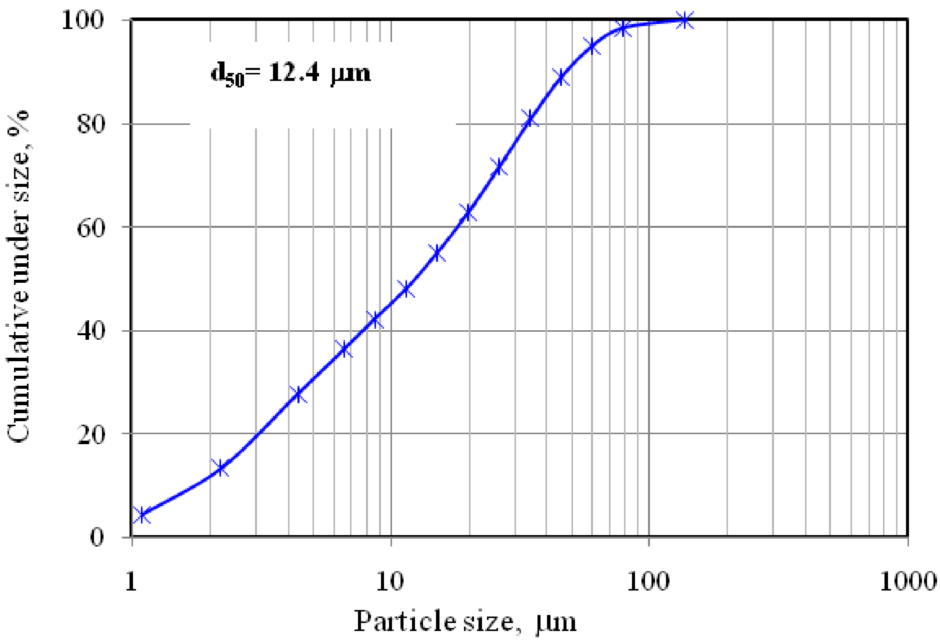

Fig.3: Particle Size Distribution of CFBC (ESP ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

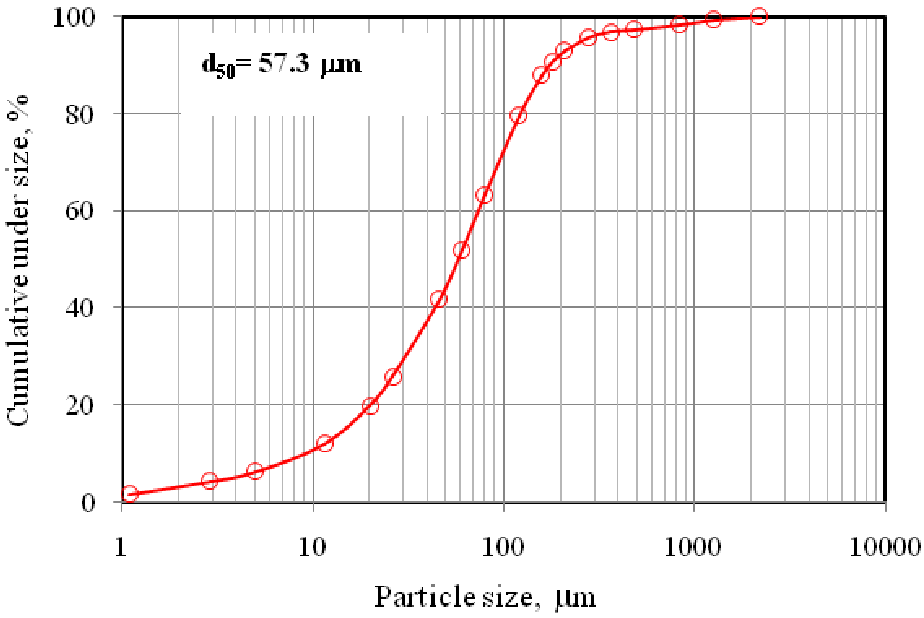

Fig.4: Particle Size Distribution of CFBC (Economizer ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

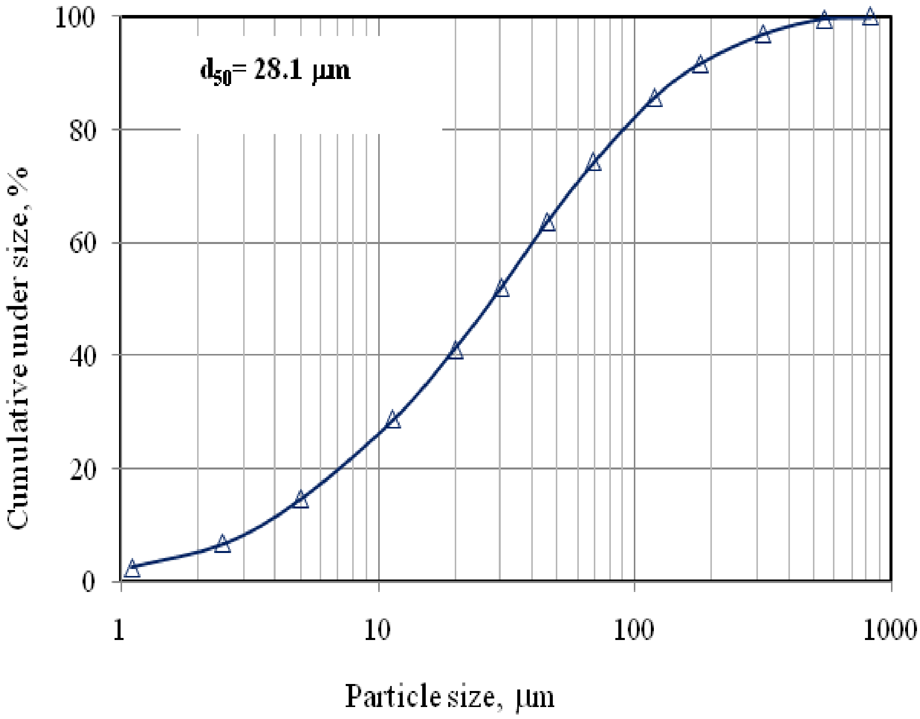

Fig.5: Particle Size Distribution of AFBC (ESP) ash samples (Bhushan Power & Steel Ltd.)

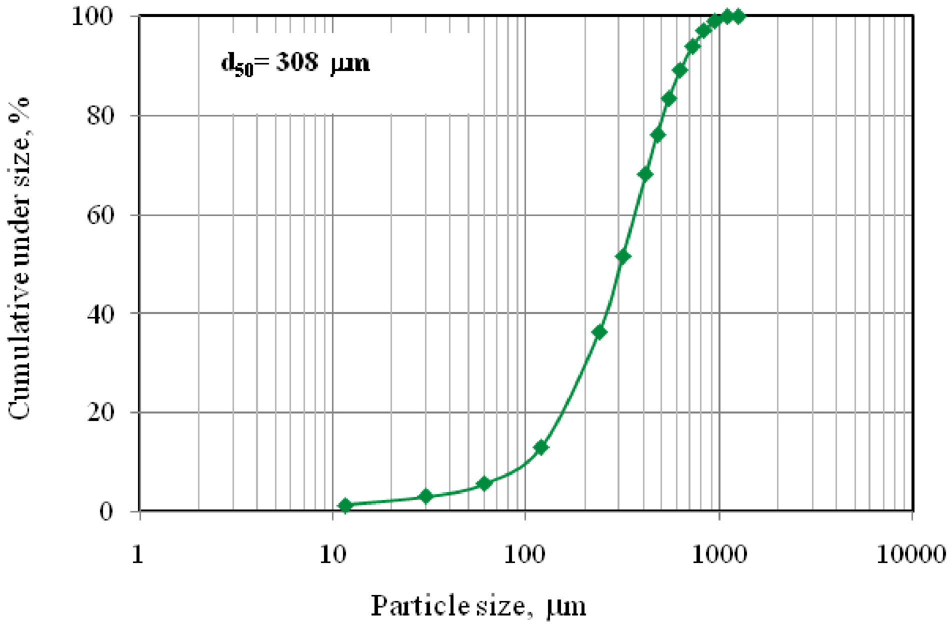

Fig.6: Particle Size Distribution of AFBC (APH ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

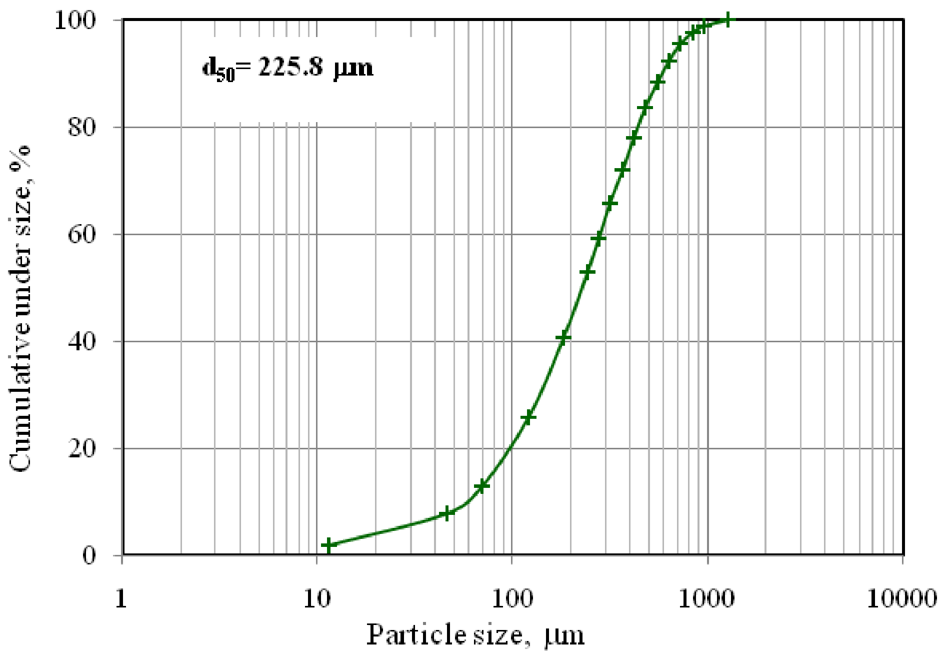

Fig.7: Particle Size Distribution of AFBC (Economizer ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

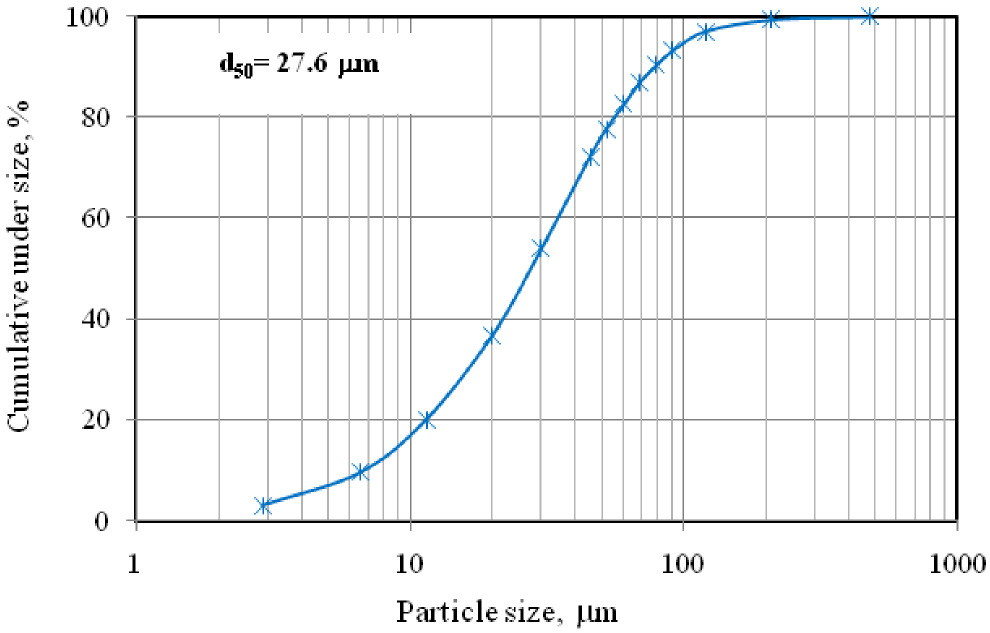

Fig.8: Particle Size Distribution of WHRB ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

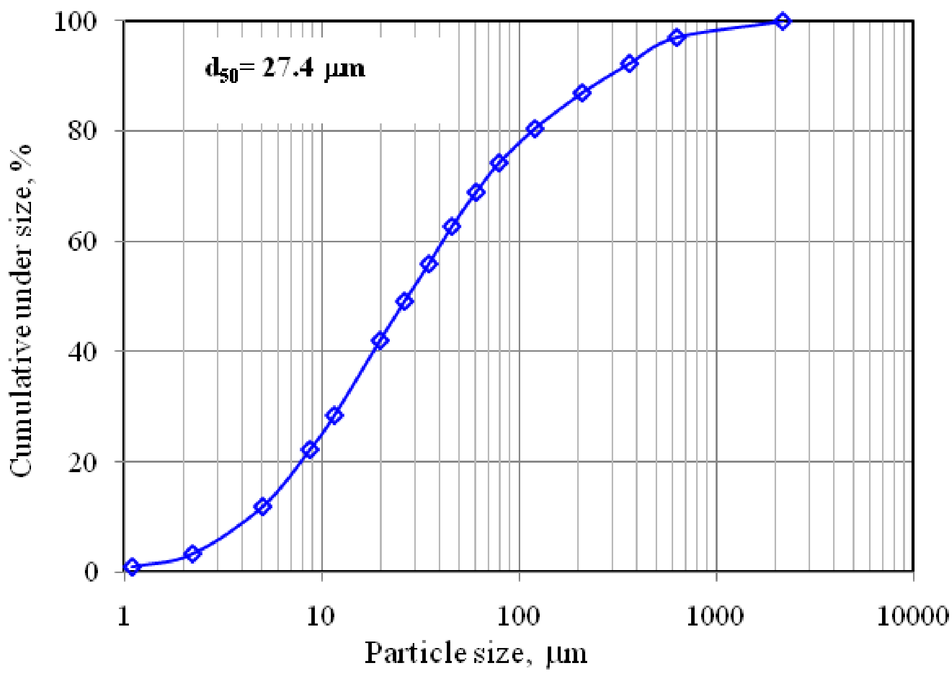

Fig.9: Particle Size Distribution of de-dusting ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

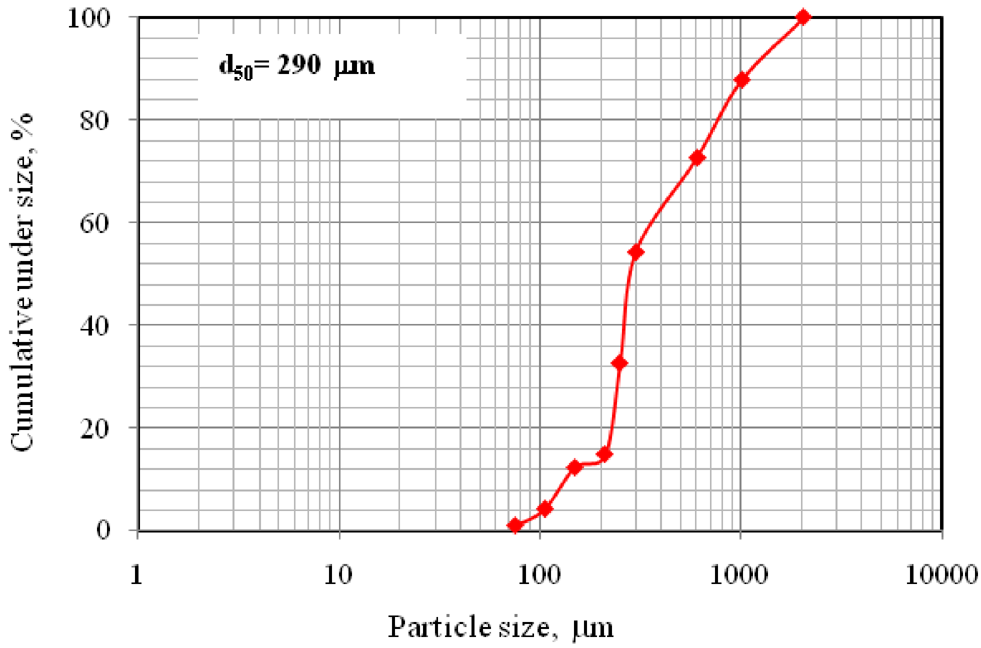

Fig.10: Particle Size Distribution of CFBC (Bed ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

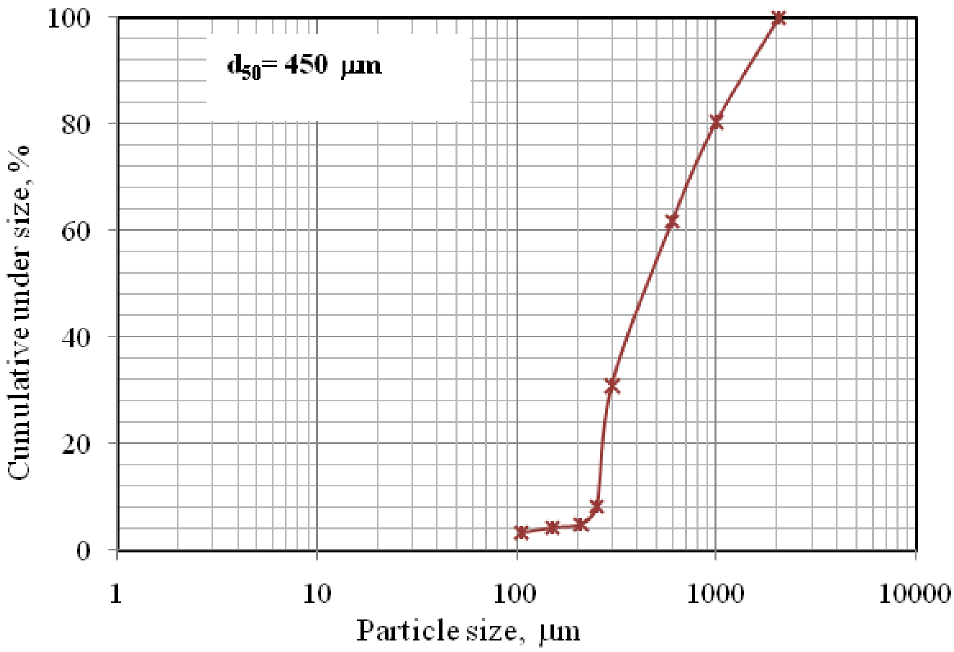

Fig.11: Particle Size Distribution of AFBC (Bed ash) ash samples

(Bhushan Power & Steel Ltd., Rengali, Sambalpur)

Table 3: Particle Size Distribution of M/s BPSL ash samples, Pumping Station 1

Particle size (μm)	Cumulative undersize (%)
1.1	1.6
2.5	5.0
5	11.2
11.5	25.2
20	39.1
28.9	**50.0**
30.2	51.3
45.7	63.0
69.2	72.5
120.2	80.9
182	85.9
316.2	92.6
549.5	98.1
1096.5	100

Table 4: Particle Size Distribution of M/s BPSL ash samples, Pumping Station 2

Particle size (μm)	Cumulative undersize (%)
1.1	3.7
2.5	9.3
5	16.1
11.5	26.5
20	36.4
30.2	46.1
35.2	**50**
45.7	56.9
69.2	67
120.2	77.3
182	83.1
316.2	90.4
549.5	97.1
1096.5	100

Table 5: Particle Size Distribution of CFBC (ESP ash) ash samples

Particle size (µm)	Cumulative undersize (%)
1.1	4.5
2.2	13.4
4.4	27.7
6.6	36.3
8.7	42.1
11.5	48.1
12.4	**50.0**
15.1	54.9
20	62.9
26.3	71.8
34.7	81.0
45.7	89.1
60.3	95
79.4	98.4
138	100

Table 6: Particle Size Distribution of CFBC (Economizer ash) ash samples

Particle size (µm)	Cumulative undersize (%)
1.1	1.8
2.9	4.4
5	6.4
11.5	12.1
20	20.0
26.3	26.0
45.7	41.9
57.3	**50.0**
60.3	52.1
79.4	63.4
120.2	79.7
158.5	87.9
182	90.9
208.9	93.0
275.4	95.6
363.1	96.8
478.6	97.4
831.8	98.3
1258.9	99.3
2187.8	100

Table 7: Particle Size Distribution of AFBC (ESP) ash samples

Particle size (µm)	Cumulative undersize (%)
1.1	2.5
2.5	6.8
5	14.7
11.5	28.8
20	41.1
30.2	52
45.7	63.6
69.2	74.3
120.2	85.7
182	91.7
316.2	96.9
549.5	99.6
831.8	100

Table 8: Particle Size Distribution of AFBC (APH ash) ash samples

Particle size (µm)	Cumulative undersize (%)
11.5	1.3
30.2	3.0
60.3	5.6
120.2	13.1
239.9	36.2
308	**50.0**
316.2	51.5
416.9	68.2
478.6	76.1
549.5	83.2
631	89.2
724.4	93.8
831.8	97.0
955	99.0
1096.5	99.8
1258.9	100

Table 9: Particle Size Distribution of AFBC (Economizer ash) ash samples

Particle size (μm)	Cumulative undersize (%)
11.5	1.8
45.7	7.7
69.2	12.9
120.2	25.7
182	40.7
225.8	**50.0**
239.8	52.8
275.4	59.2
316.2	65.7
363.1	72.1
416.9	78.1
478.6	83.7
549.5	88.5
631	92.4
724.4	95.5
831.8	97.7
955	99.0
1258.9	100

Table 10: Particle Size Distribution of WHRB ash samples

Particle size (μm)	Cumulative undersize (%)
2.9	3.1
6.6	9.7
11.5	20.0
20	36.8
27.6	**50.0**
30.2	54.0
45.7	72.2
52.5	77.6
60.3	82.6
69.2	86.9
79.4	90.4
91.2	93.3
120.2	97.0
208.9	99.4
478.6	100

Table 11: Particle Size Distribution of De-dusting ash samples

Particle size (μm)	Cumulative undersize (%)
1.1	1.1
2.2	3.3
5	11.8
8.7	22.1
11.5	28.3
19.6	41.9
26.3	49.0
27.4	50.0
34.7	56.0
45.7	62.5
60.3	69.0
79.4	74.2
120.3	80.4
208.9	86.8
363.1	92.3
631	96.9
2188	100

Table 12: Particle Size Distribution of CFBC Bed ash samples

Particle size (μm)	Cumulative undersize (%)
75	0.9
105	4.1
150	12.4
210	14.7
250	32.7
290	**50**
300	54.1
600	72.6
1003	87.8
2057	100

Table 13: Particle Size Distribution of AFBC Bed ash samples

Particle size (μm)	Cumulative undersize (%)
105	3.5
150	4.3
210	4.9
250	8.3
300	30.9
450	**50**
600	61.9
1003	80.4
2057	100

2.4Particle density

The particle density of ash samples was carried out using standard specific gravity bottles following standard procedure. The material densities of individual ash samples as well mixed ash samples for the proposed two high concentration ash slurry Pumping stations 1 & 2 are given in Table-14.

Table-14: Particle density of ash samples, BPSL, Rengali, Sambalpur

Sl.No	Type of ash	Particle density, Kg/m^3
1	Proposed Pumping Station 1	2761
2	Proposed Pumping Station 2	2563
3	CFBC ESP ash	2602
4	CFBC Economizer ash	2555
5	CFBC Bed ash	2497
6	AFBC ESP ash	2509
7	AFBC Economizer ash	2467
8	AFBC Bed ash	2531
9	AFBC Air Pre-heater ash	2511
10	WHRB ash	2612
11	De-dusting ash	2523

2.5 pH of ash slurry

The two ash samples for the proposed high concentration pumping stations-1 and 2 were used to ascertain the trend of variation of pH values with mixing time. Ash slurries were prepared at 60% solids weight concentrations using distilled water as medium. The results of the mixing experiment conducted at C_W=60% for the two ash samples are given in Tables 15 &16 and are plotted in Fig. 12.

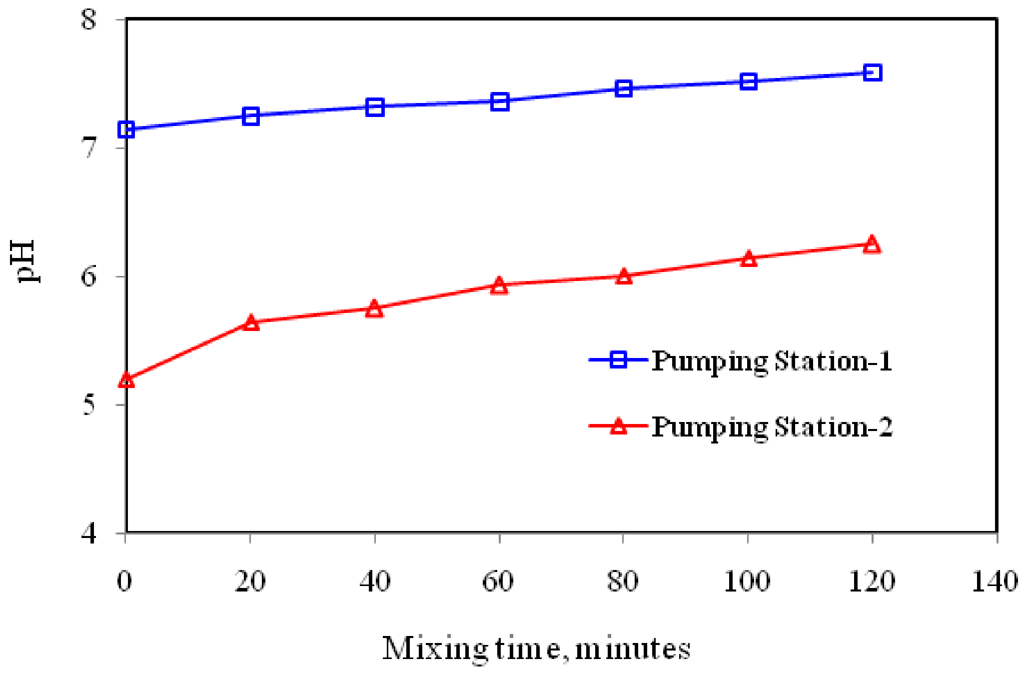

Fig. 12: Variation of pH with mixing time of BPSL ash slurry samples in distilled water medium (pH=6.4) for the proposed 2 HCSD pumping stations, C_W=60%

Table-15: Variation of pH with mixing time for BPSL ash slurry samples, Pumping Station-1, C_W=60%

Mixing time, minutes	pH of ash slurry
0	7.15
20	7.25
40	7.32
60	7.36
80	7.47
100	7.52
120	7.59

Table-16: Variation of pH with mixing time for BPSL ash slurry samples, Pumping Station-2, Cw=60%

Mixing time, minutes	pH of ash slurry
0	5.2
20	5.65
40	5.75
60	5.93
80	6.01
100	6.15
120	6.25

From the tables 15 and 16 it is seen that the initial pH of Pumping Station-1 ash sample was alkaline in nature with a pH value of 7.15 whereas the pH of Pumping Station-2 ash samples was acidic with a pH value of 5.2. But with the addition of distilled water and on gradual mixing time, the slurry pH for both the ash samples increases as indicated from Fig.12. The slurry pH of Pumping Station ash samples 1 and 2 achieve a value of 7.59 and 6.25 respectively after a total mixing time of 120 minutes.

2.6 Maximum static settled concentration (sedimentation) tests

The maximum static settled concentration of the ash samples for the proposed ash slurry pumping stations 1 and 2 were carried out to ascertain the limiting concentration of the ash slurry maintaining flowability. The proposed ash slurry pumping station 1 consists of ash from Silo-1, Silo-2 and Silo-3. Similarly, the ash slurry pumping station 2 consists of ash from Silo-4 to Silo-13. The data obtained on maximum settled concentrations for the two pumping stations 1 & 2 are given in Tables 17 and 18 and are plotted in Figs. 13 & 14.

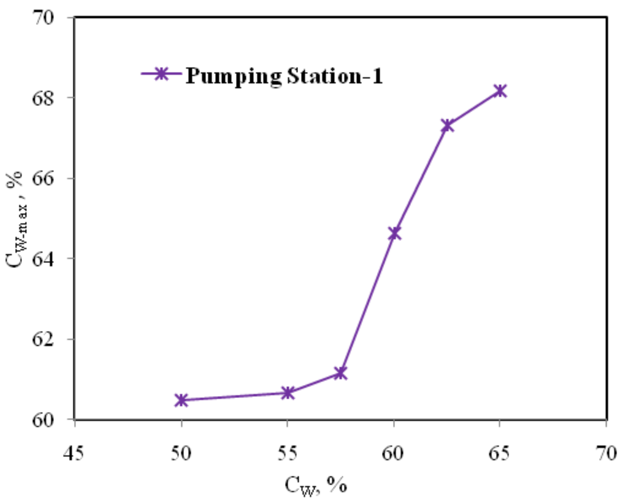

Fig. 13: Maximum settled concentration at different slurry concentration by weight.

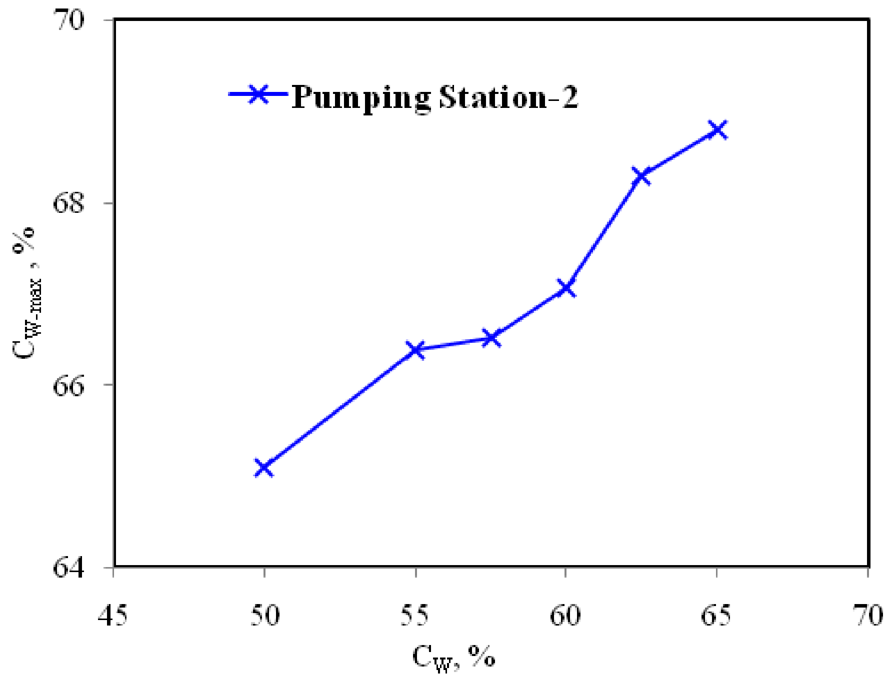

Fig. 14: Maximum settled concentration at different slurry concentration by weight.

Table 17: Maximum settled concentration (sedimentation test) data for the proposed ash slurry pumping station 1

C_W (%)	$C_{W\text{-max}}$ (%)
50	60.48
55	60.17
57.5	61.16
60	64.63
62.5	67.33
65	68.18

Table 18: Maximum settled concentration (sedimentation test) data for the proposed ash slurry pumping station 2

C_W (%)	$C_{W\text{-}max}$ (%)
50	65.1
55	66.38
57.5	66.51
60	67.06
62.5	68.3
65	68.8

It is seen from the tables that the ash samples of the pumping station 2 achieves higher value of $C_{W\text{-}max}$ as compared to that of pumping station 1. Therefore, it is possible to transport the ash slurry of pumping station 2 at a higher solids concentration than that of pumping station 1.

CHAPTER 3

RHEOLOGICAL STUDIES

3.1 Introduction

The rheological studies for the two ash samples (proposed ash slurry pumping stations 1 & 2) were conducted using a Haake rheometer (Model: RheoStress 1) in the slurry concentration range of 50-65% by weight. The shear rate-shear stress data obtained for the two ash samples at different weight concentrations are given in Tables 19 to 27 and the rheogram of two ash samples are shown in Figs. 15 & 16.

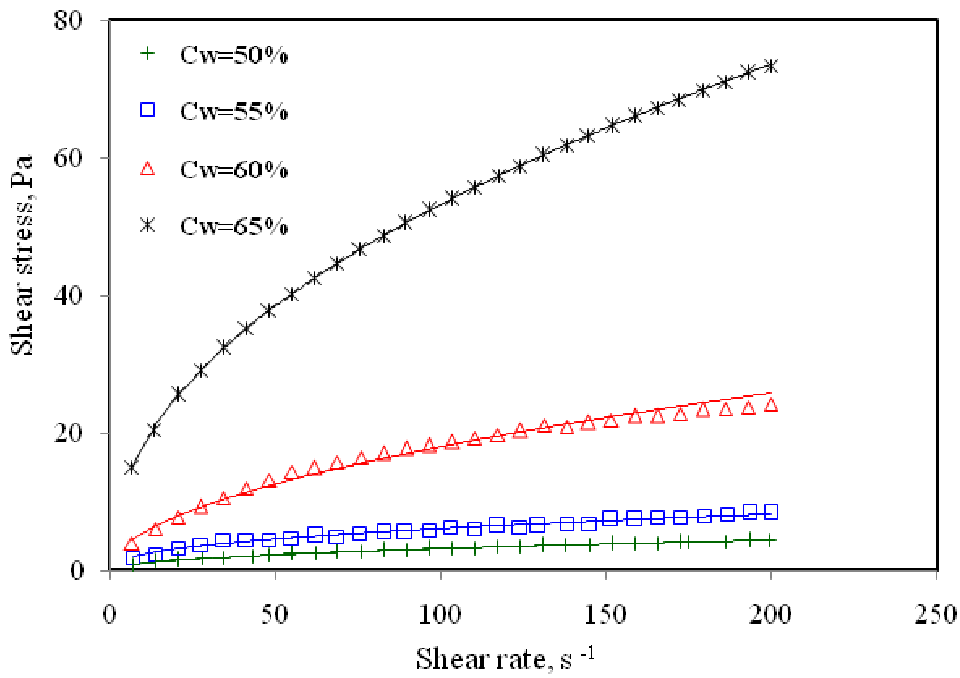

Fig.15: Rheogram of BPSL ash slurry at different wt. concentrations (Proposed Pumping Station – 1)

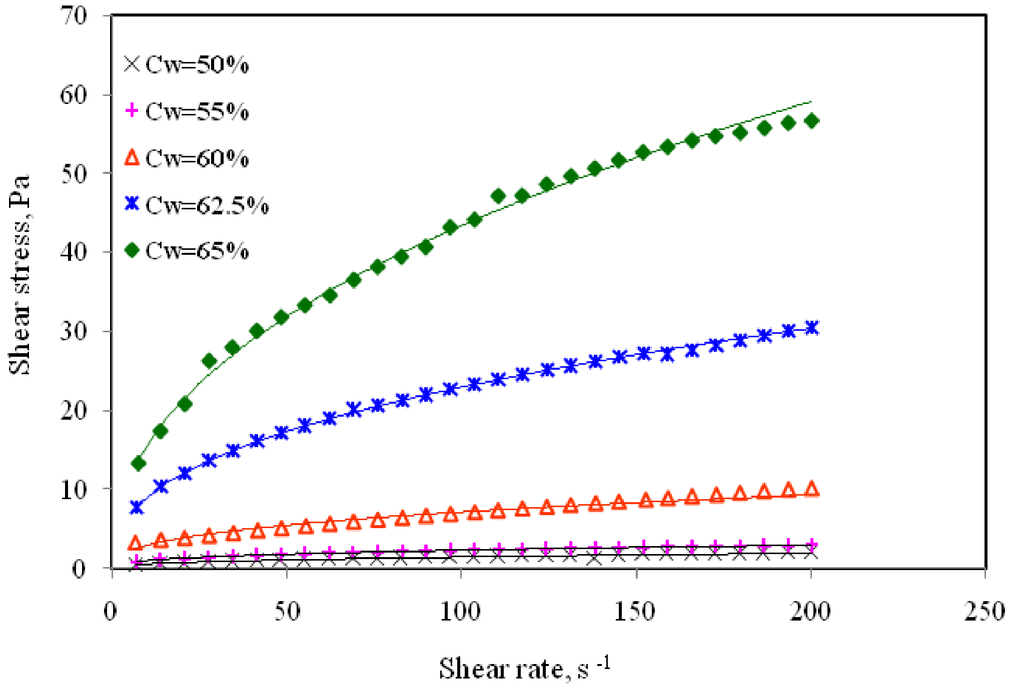

Fig.16: Rheogram of BPSL ash slurry at different wt. concentrations (Proposed Pumping Station – 2)

It is seen from the Figs. 15 and 16 that the shear stress-shear rate data quite well fitted to Power law model in the slurry concentration range of 50-65% by weight. The flow characteristics of the two ash samples indicated shear thinning behaviour or "Pseudo-plastic" behaviour which is observed from the shape of two rehograms. The flow pattern is non-Newtonian at these concentrations. The power law model that fitted the experimental data in the studied range of slurry concentrations of 50-65% by weight for the two ash samples can be represented by:

$$\boxed{\tau = K\gamma^n}$$

where τ (pa) is the shear stress,

γ (s^{-1}) is the shear rate,

'n' is the flow behaviour index

and 'K' is the consistency index.

Table-19: Rheology of BPSL ash slurry, Pumping Station-1, C_W=50%

Shear rate, s^{-1}	Shear stress, Pa	Apparent viscosity, Pas.
6.877	0.872	0.127
13.74	1.204	0.088
20.89	1.472	0.0704
27.94	1.778	0.064
34.55	1.89	0.0547
43.27	2.105	0.0486
48.39	2.22	0.0458
55.18	2.364	0.043
62.3	2.51	0.0402
68.56	2.62	0.0382
75.89	2.753	0.036
82.84	2.871	0.0346
89.7	2.982	0.0332
96.64	3.091	0.0319
103.6	3.195	0.0308
110.4	3.294	0.0298
117.3	3.391	0.0289
124.3	3.486	0.028
131.2	3.577	0.027
138	3.66	0.0265
145.1	3.754	0.0258
151.8	3.83	0.0252
158.7	3.918	0.0247
165.6	3.998	0.024
172.5	4.077	0.0236
175.1	4.106	0.0234
186.3	4.23	0.0227
193.4	4.306	0.022
199.6	4.373	0.022

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 0.348, n = 0.48

Table-20: Rheology of BPSL ash slurry, Pumping Station-1, C_W=55%

Shear rate, s^{-1}	Shear stress, Pa	Apparent viscosity, as.
6.935	1.867	0.27
13.99	2.3	0.164
20.72	3.2	0.154
27.76	3.62	0.13
34.64	4.36	0.125
41.57	4.364	0.105
48.1	4.335	0.09
55.16	4.68	0.085
62.54	4.98	0.077
68.91	4.934	0.072
75.68	5.381	0.071
82.79	5.428	0.066
89.5	5.485	0.061
96.7	5.8	0.06
103	6.31	0.061
110.4	6.05	0.055
117.4	6.385	0.054
124.3	6.318	0.051
129.7	6.44	0.0496
138.2	6.764	0.0489
145.3	6.723	0.0462
151.7	7.317	0.0482
159	7.31	0.046
165.6	7.682	0.0463
172.6	7.776	0.045
179.7	7.963	0.044
186.7	8.125	0.0435
193.4	8.325	0.043
200	8.281	0.0414

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 0.82, n = 0.433

Table-21: Rheology of BPSL ash slurry, Pumping Station-1, C_W=60%

Shear rate, **s** $^{-1}$	Shear stress, Pa	Apparent viscosity, as.
6.797	3.993	0.587
13.81	6.019	0.436
20.6	7.703	0.373
27.49	9.223	0.335
34.45	10.47	0.304
41.27	11.92	0.288
48.42	13.17	0.277
55.16	14.24	0.258
62.03	14.89	0.24
68.92	15.67	0.227
75.93	16.49	0.217
82.95	16.99	0.205
89.72	17.72	0.198
96.52	18.2	0.186
103.7	18.66	0.18
110.4	19.3	0.175
117.4	19.72	0.168
124.2	20.29	0.163
131.3	21.09	0.16
138.3	20.97	0.152
144.9	21.47	0.148
151.7	21.81	0.144
158.7	22.44	0.141
165.6	22.45	0.135
172.5	22.76	0.132
179.4	23.36	0.13
186.3	23.56	0.126
193.2	23.69	0.123
199.8	24.16	0.121

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 1.636, n = 0.52

Table-22: Rheology of BPSL ash slurry, Pumping Station-1, C_W=65%

Shear rate, s^{-1}	Shear stress, Pa	Apparent viscosity, as.
6.483	15.02	2.316
13.27	20.36	1.53
20.62	25.49	1.236
27.61	29.21	1.06
34.38	32.35	0.941
41.46	35.3	0.851
48.3	37.9	0.784
54.88	40.23	0.733
61.96	42.57	0.687
68.84	44.71	0.649
75.82	46.77	0.616
82.86	48.74	0.588
89.32	50.48	0.565
96.68	52.38	0.541
103.3	54.02	0.522
110.4	55.72	0.504
117.5	57.36	0.49
124.1	58.84	0.474
131	60.34	0.46
138.1	61.84	0.447
144.8	63.3	0.437
151.8	64.63	0.425
158.7	65.98	0.415
165.5	67.3	0.406
172.1	68.52	0.398
179.5	69.9	0.389
186.4	71.12	0.381
193.3	72.34	0.374
200	73.5	0.367

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 6.206, n = 0.466

Table-23: Rheology of BPSL ash slurry, Pumping Station-2, C_W=50%

Shear rate, s^{-1}	Shear stress, Pa	Apparent viscosity, as.
7.033	0.428	0.06
13.83	0.584	0.042
20.8	0.705	0.038
27.7	0.805	0.029
34.57	0.892	0.026
41.54	0.97	0.023
48.18	1.04	0.021
55.15	1.106	0.02
62.12	1.168	0.0188
69.09	1.227	0.0177
75.9	1.281	0.0168
82.7	1.333	0.016
89.68	1.383	0.0154
96.65	1.432	0.0148
103.5	1.478	0.0142
110.4	1.522	0.0137
117.4	1.566	0.0133
124.2	1.607	0.013
131	1.647	0.0125
138	1.165	0.0084
144.8	1.725	0.012
151.8	1.763	0.0116
158.8	1.8	0.0114
165.7	1.83	0.011
172.6	1.87	0.0108
179.5	1.9	0.01
186.3	1.938	0.0104
193.3	1.971	0.01
200	2.003	0.01

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 0.179, n = 0.45

Table-24: Rheology of BPSL ash slurry, Pumping Station-2, C_W=55%

Shear rate, s^{-1}	Shear stress, Pa	Apparent viscosity, as.
7.163	0.843	0.118
13.79	1.074	0.078
20.76	1.25	0.06
27.73	1.39	0.05
34.7	1.512	0.0435
41.51	1.616	0.0389
48.48	1.711	0.0353
55.28	1.8	0.033
62.25	1.877	0.03
69.05	1.95	0.028
76.03	2.02	0.0265
83	2.088	0.0251
89.81	2.15	0.0239
96.78	2.21	0.0228
103.6	2.27	0.0219
110.6	2.32	0.021
117.5	2.374	0.02
124.2	2.424	0.0195
131.1	2.473	0.0188
138.1	2.521	0.0182
145.1	2.567	0.0177
151.9	2.611	0.0172
158.9	2.65	0.0166
165.9	2.7	0.0162
172.7	2.74	0.0158
179.5	2.78	0.0154
186.5	2.81	0.015
193.5	2.84	0.0147
200	2.88	0.014

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 0.407, n = 0.37

Table-25: Rheology of BPSL ash slurry, Pumping Station-2, C_W=60%

Shear rate, $\mathbf{s}^{-1}$	Shear stress, Pa	Apparent viscosity, as.
6.597	3.174	0.481
13.92	3.52	0.253
20.72	3.754	0.181
27.69	4.08	0.147
34.66	4.39	0.126
41.63	4.707	0.113
48.43	4.993	0.103
55.4	5.278	0.0952
62.21	5.557	0.0893
69.01	5.804	0.0841
75.98	6.075	0.08
82.99	6.311	0.076
89.76	6.553	0.073
96.74	6.792	0.07
103.7	7.024	0.068
110.3	7.249	0.066
117.3	7.478	0.064
124.3	7.708	0.062
131.1	7.921	0.06
138.3	8.147	0.059
144.9	8.342	0.056
152.6	8.591	0.0562
158.9	8.789	0.0553
165.8	9.022	0.0544
172.8	9.242	0.0534
179.5	9.451	0.0526
186.4	9.659	0.0518
193.4	9.881	0.051
200	10.04	0.05

Rheological Model fitted :

$\tau = K\gamma^{n}$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 1.22, n = 0.382

Table-26: Rheology of BPSL ash slurry, Pumping Station-2, C_W=62.5%

Shear rate, **s** $^{-1}$	Shear stress, Pa	Apparent viscosity, as.
7.159	7.78	1.086
14.01	10.41	0.743
20.79	12.1	0.582
27.76	13.69	0.493
34.73	14.99	0.432
41.54	16.12	0.388
48.51	17.16	0.353
55.14	18.08	0.327
62.12	18.97	0.305
69.09	20.13	0.291
75.89	20.6	0.271
83.03	21.34	0.257
89.67	22.02	0.245
96.65	22.7	0.235
103.6	23.34	0.225
110.4	23.95	0.217
117.4	24.56	0.209
124.4	25.14	0.202
131.2	25.7	0.196
138.2	26.24	0.19
145.1	26.76	0.184
152	27.2	0.178
158.8	27.11	0.171
165.7	27.71	0.167
172.7	28.32	0.164
179.5	28.89	0.161
186.5	29.52	0.158
193.5	30.07	0.155
200	30.48	0.152

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 3.561 , n = 0.404

Table-27: Rheology of BPSL ash slurry, Pumping Station-2, C_W=65%

Shear rate, $\mathbf{s}^{-1}$	Shear stress, Pa	Apparent viscosity, as.
7.51	13.24	1.763
13.81	17.34	1.26
20.76	20.77	1
27.73	26.25	0.095
34.35	27.95	0.813
41.34	30.06	0.727
48.32	31.8	0.658
55.12	33.3	0.604
62.28	34.56	0.555
69.06	36.52	0.529
75.88	38.18	0.503
82.68	39.47	0.477
89.65	40.7	0.454
96.62	43.2	0.447
103.6	44.18	0.426
110.4	47.18	0.427
117.2	47.22	0.403
124.2	48.64	0.392
131.2	49.69	0.379
138	50.68	0.367
144.8	51.71	0.357
151.8	52.72	0.347
158.8	53.4	0.336
165.8	54.22	0.327
172.5	54.77	0.318
179.6	55.21	0.307
186.5	55.82	0.299
193.3	56.44	0.292
200	56.73	0.284

Rheological Model fitted :

$\tau = K\gamma^n$ (Power Law model),

Where $\tau =$ Shear stress, Pa, γ =Shear rate, Sec^{-1}, K =Consistency parameter,

$n =$ Flow behaviour index

K = 5.563, n = 0.446

Chapter 4

PIPE LOOP TEST STUDIES

4.1 Description of the test loop set-up

The pipe loop tests were conducted for the ash samples using the facility of High Concentration Test Loop at IIMT, Bhubaneswar. The high concentration test loop consists of 50 mm and 100 mm ND pipes of 16 meter length each. A progressive cavity pump (Mono Pump) having throughput of 50 m^3/hr is driven by a 3-phase induction geared motor of 30KW capacity. The slurry of required concentration is prepared by a helical ribbon mixer (1000 liter tank capacity) with variable frequency drive installed in the system. The slurry pumped through the pipelines returns in the loop and freely discharges into the slurry hopper which has a temporary storage capacity of 0.8 m^3. A by-pass pipeline has been provided at the discharge point of the pump and discharges the slurry into the slurry hopper during start up period for uniform mixing of the slurry. Control of pipeline velocity is obtained through the use of Variable Frequency Drive (VFD) of ABB make. By operating the VFD connected to the motor, the pump speed can be controlled. The volume flow rate of slurry in the pipelines is measured with the help of magnetic flow meters (Make: Krohne Marshal) mounted vertically in the 50 mm and 100mm dia sections. Mercury manometers were used to measure the head loss of slurry. The pressure taping points spaced at 3.5 m distance in the return line are connected through the settling chambers meant to trap slurry preventing it to enter the pressure transmitting lines. The high concentration test loop shown in figure 17.

4.2 Pipe loop experiments with BPSL ash samples

As per the work order of M/s BPSL, Sambalpur, the pipe loop tests were conducted for the two ash samples (namely Pumping Station-1 and Pumping Station-2) in the slurry concentration range of 50-65% by weight. The pipe loop tests data in 50 mm and 100 mm diameter pipes for the two ash samples are presented in Tables 28- 45. The velocity versus head loss plots in these two candidate pipes at slurry concentrations range of 50-65% for the two ash samples are given in Figs. 18-21.

It is seen from the Figs. 18-21 that the ash slurry samples of the proposed HCSD pumping station-1 incurred higher pressure drop than that of ash slurry samples of pumping station -2. While designing the two ash slurry disposal pipelines, these data will be quite useful to provide scale up designs for higher size pipelines.

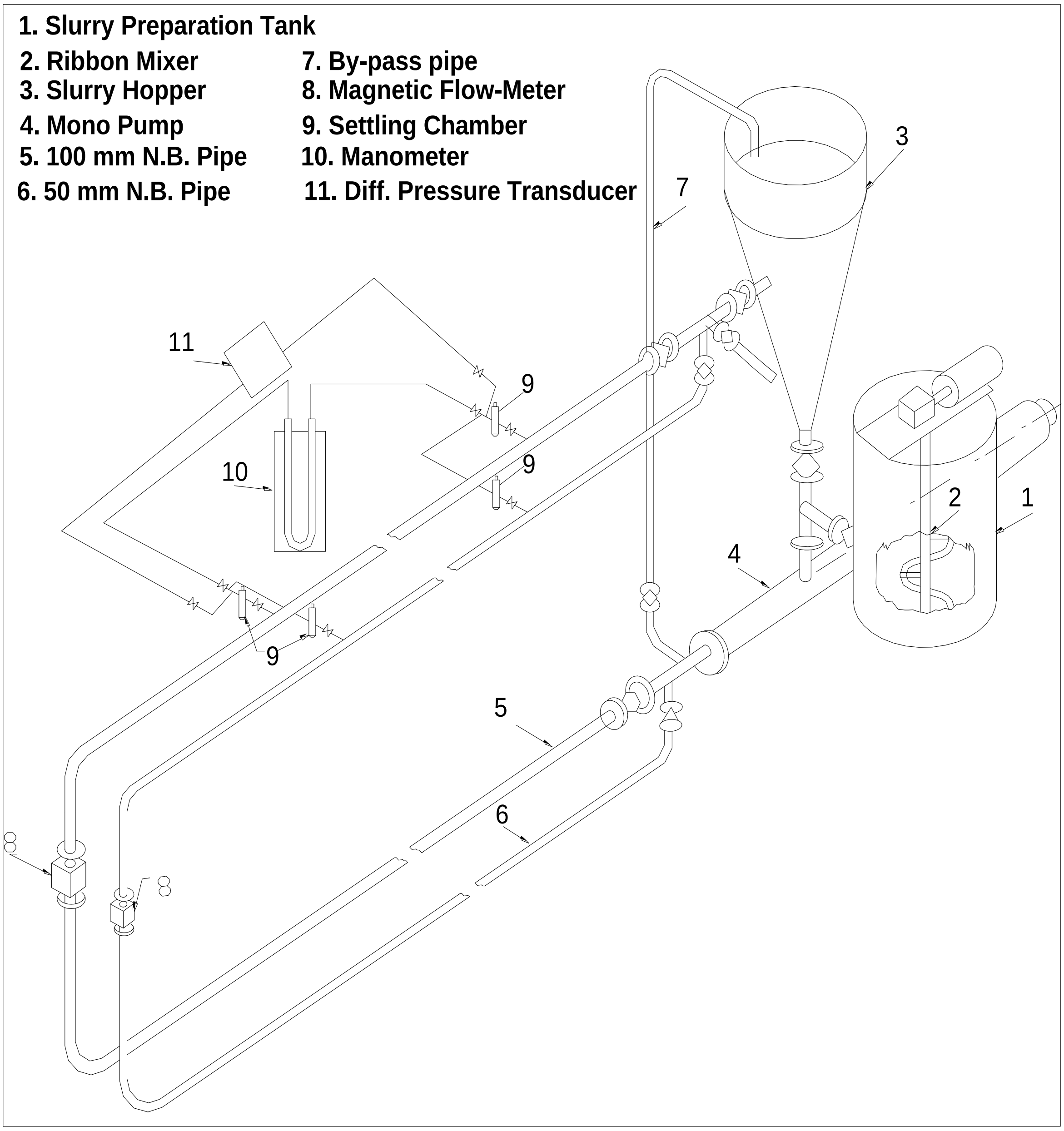

Fig.17: High Concentration Slurry Test Loop facility at IMMT, Bhubaneswar

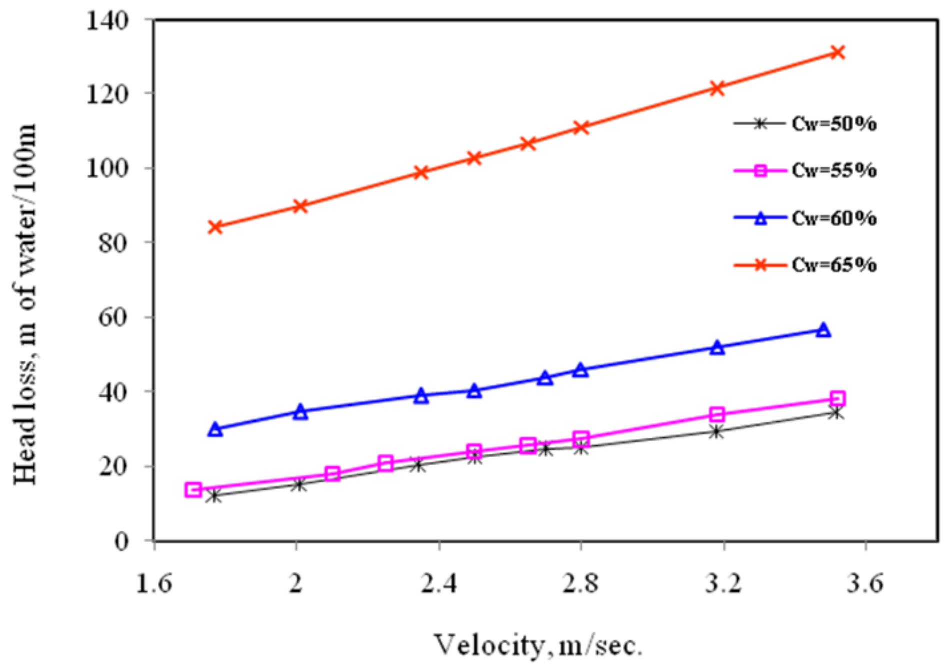

Fig.18: Velocity vs. head loss of BPSL ash slurry in 50 mm dia pipe

(Proposed HCSD Pumping Station-1)

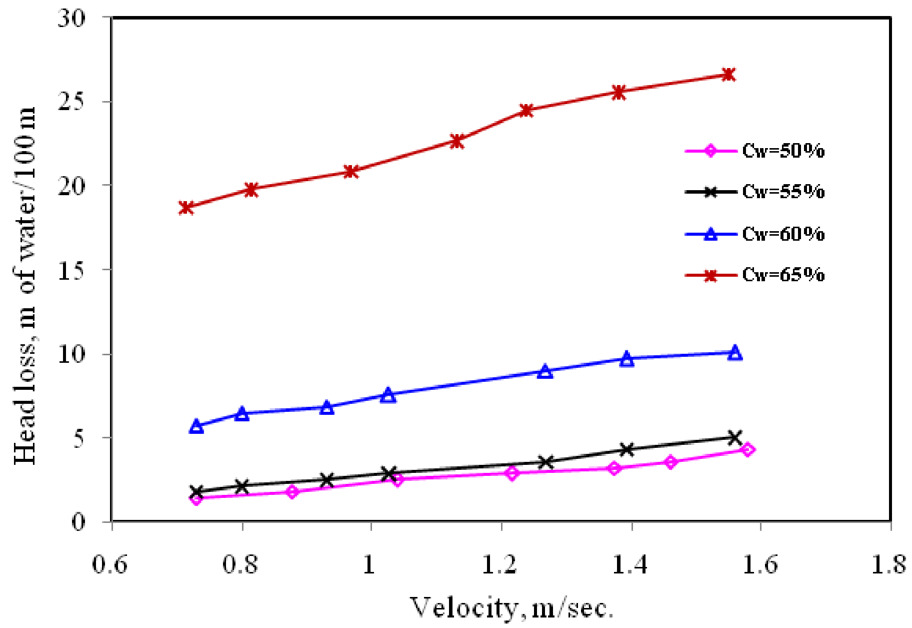

Fig.19: Velocity vs. head loss of BPSL ash slurry in 100 mm dia pipe (Proposed HCSD Pumping Station-1)

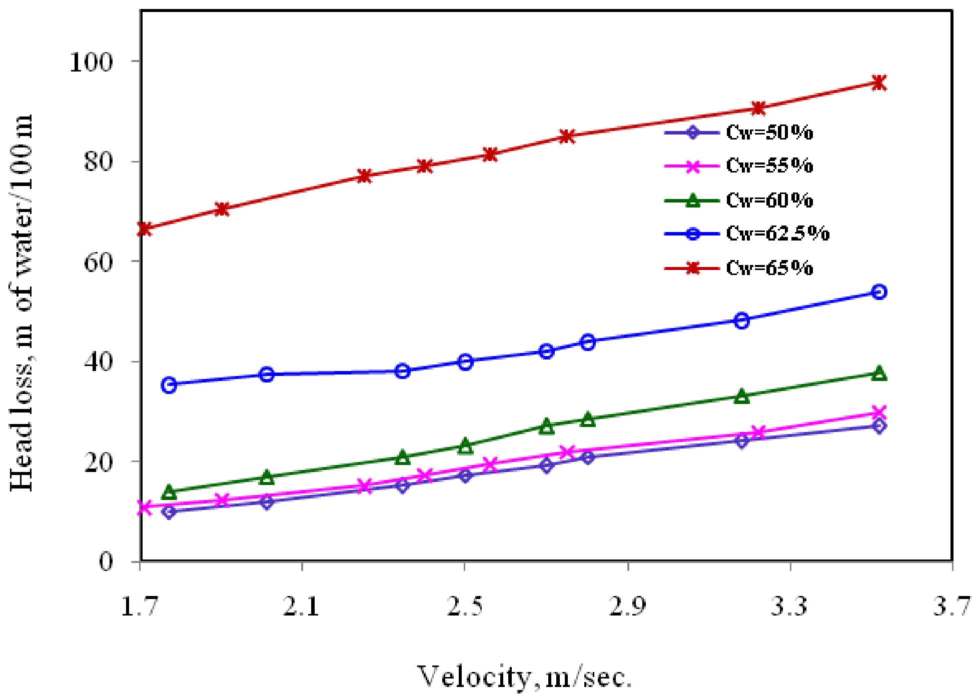

Fig.20: Velocity vs. head loss of BPSL ash slurry in 50 mm dia pipe (Proposed HCSD Pumping Station-2)

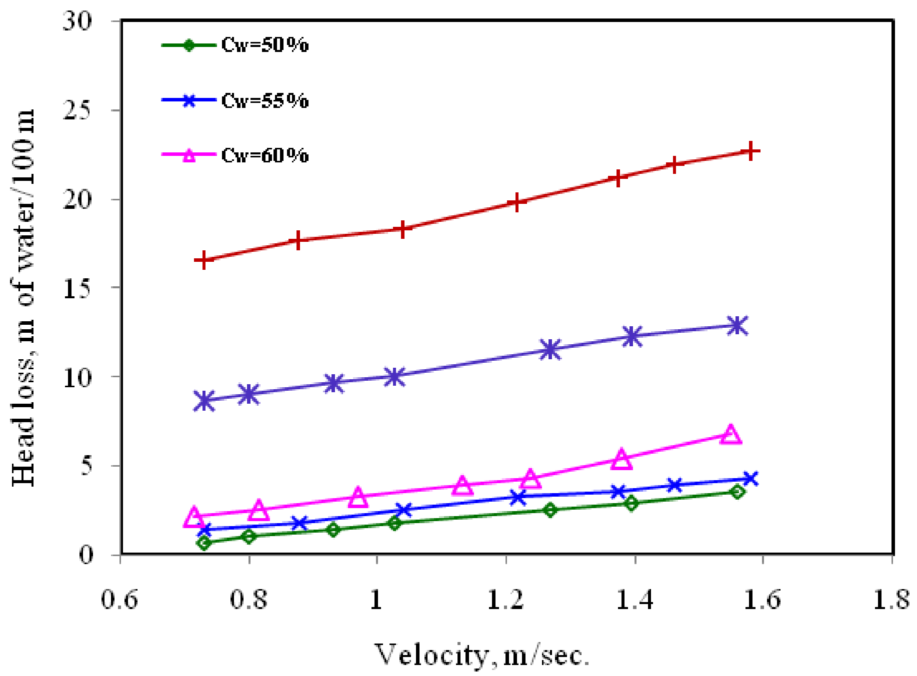

Fig.21: Velocity vs. head loss of BPSL ash slurry in 100 mm dia pipe (Proposed HCSD Pumping Station-2)

Table-28: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1468.2 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 50%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	34	12.24
13.4	2.01	42	15.12
15.6	2.345	56	20.16
16.6	2.5	62	22.32
18	2.7	68	24.48
18.6	2.8	70	25.2
21.2	3.18	82	29.52
23.4	3.52	96	34.56

Table-29: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1540.3 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 55%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.4	1.71	38	13.68
14	2.1	50	18
15	2.25	58	20.9
16.6	2.5	67	24.12
17.6	2.65	71	25.56
18.6	2.8	78	27.36
21.2	3.18	94	33.84
23.4	3.52	106	38.16

Table-30: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1620 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 60%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	84	30.24
13.4	2.01	96	34.56
16	2.35	108	38.88
16.2	2.5	112	40.32
18	2.7	122	43.92
18.6	2.8	128	46.08
21.1	3.18	145	52.2
23.2	3.48	158	56.88

Table-31: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1708.2 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 65%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	234	84.24
13.4	2.01	250	90
16	2.35	275	99
16.3	2.5	286	102.96
17.3	2.65	296	106.8
18.6	2.8	308	111
21.1	3.18	338	121.6
23.2	3.52	365	131.4

Table-32: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1468.2 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 50%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	4	1.44
25.8	0.8775	5	1.8
30.6	1.04	7	2.52
35.8	1.217	8	2.88
40.4	1.374	9	3.24
43	1.46	10	3.6
46.4	1.58	12	4.32
21.5	0.73	4	1.44

Table-33: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1540.3 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 55%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	5	1.8
23.5	0.8	6	2.16
27.4	0.93	7	2.52
30.3	1.026	8	2.88
37.3	1.268	10	3.6
41	1.393	12	4.32
46	1.56	14	5.04

Table-34: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1620 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 60%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	16	5.76
23.5	0.8	18	6.5
27.4	0.93	19	6.84
30.3	1.026	21	7.56
37.3	1.268	25	9
41	1.393	27	9.72
46	1.56	28	10.08

Table-35: Pipe Loop test data for the proposed HCSD Pumping Station-1

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1708 kg/m^3

Material: Mixed ash samples of Silo 1+Silo 2 +Silo 3

Slurry concentration: 65%

Specific gravity of solids: 2.761

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21	0.714	52	18.72
24	0.815	55	19.8
28.5	0.968	58	20.88
33.3	1.132	63	22.68
36.4	1.237	68	24.48
40.6	1.38	71	25.56
45.8	1.55	74	26.64

Table-36: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1438.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 50%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	28	10.08
13.4	2.01	33	11.88
15.6	2.345	42	15.12
16.6	2.5	48	17.28
18	2.7	53	19.08
18.6	2.8	58	20.88
21.2	3.18	67	24.12
23.4	3.52	75	27

Table-37: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1504.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 55%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.4	1.71	30	10.8
12.6	1.9	34	12.24
15	2.25	42	15.12
16	2.4	48	17.28
17	2.56	54	19.44
18.3	2.75	61	21.96
21.4	3.22	72	25.92
23.4	3.52	83	29.88

Table-38: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1577 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 60%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	39	14.04
13.4	2.01	47	16.92
15.6	2.345	58	20.88
16.6	2.5	64	23.04
18	2.7	75	27
18.6	2.8	79	28.44
21.2	3.18	92	33.12
23.4	3.52	105	37.8

Table-39: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1615.9 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 62.5%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.8	1.77	98	35.28
13.4	2.01	104	37.44
15.6	2.345	106	38.16
16.6	2.5	111	39.96
18	2.7	117	42.12
18.6	2.8	122	43.92
21.2	3.18	134	48.24
23.4	3.52	150	54

Table-40: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 50 mm

Pipe ID: 0.0485 m

Slurry Density: 1656.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 65%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
11.4	1.71	185	66.6
12.6	1.9	196	70.56
15	2.25	214	77.04
16	2.4	220	79.2
17	2.56	226	81.36
18.3	2.75	236	84.96
21.4	3.22	252	90.72
23.4	3.52	266	95.76

Table-41: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1438.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 50%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	2	0.72
23.5	0.8	3	1.08
27.4	0.93	4	1.44
30.3	1.026	5	1.8
37.3	1.268	7	2.52
41	1.393	8	2.88
46	1.56	10	3.6

Table-42: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1504.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 55%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	4	1.44
25.8	0.8775	5	1.8
30.6	1.04	7	2.52
35.8	1.217	9	3.24
40.4	1.374	10	3.6
43	1.46	11	3.96
46.4	1.58	12	4.32

Table-43: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1577 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 60%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21	0.714	6	2.16
24	0.815	7	2.52
28.5	0.968	9	3.24
33.3	1.132	11	3.96
36.4	1.237	12	4.32
40.6	1.38	15	5.4
45.8	1.55	19	6.84

Table-44: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1615.9 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 62.5%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	24	8.64
23.5	0.8	25	9
27.4	0.93	27	9.72
30.3	1.026	28	10.08
37.3	1.268	32	11.52
41	1.393	34	12.24
46	1.56	36	12.96

Table-45: Pipe Loop test data for the proposed HCSD Pumping Station-2

Pipe Size (Nominal): 100 mm

Pipe ID: 0.102 m

Slurry Density: 1656.7 kg/m^3

Material: Mixed ash samples of Silo 4 – Silo 13

Slurry concentration: 65%

Specific gravity of solids: 2.563

Slurry Temperature: 30 ^{O}C

Flow Rate, m^3/hr	Velocity, m/sec.	Head loss, mm of Hg./3.5 m	Head loss, m of water /100 m
21.5	0.73	0.73	16.56
25.8	0.8775	0.8775	17.64
30.6	1.04	1.04	18.36
35.8	1.217	1.217	19.8
40.4	1.374	1.374	21.24
43	1.46	1.46	21.96
46.4	1.58	1.58	22.68

CHAPTER 5

DESIGN PARAMETERS AND SPECIFIC POWER CONSUMPTION OF BPSL ASH SAMPLES

5.1 Introduction

In order to transport the ash slurry at high solids concentration, the various hydraulic and design parameters such as slurry head loss, solids conveying rate, specific power consumption, hydraulic power requirements, specific power consumption (SPC) etc. have been evaluated. In the present study three candidate pipes having nominal diameters of 100, 150 and 200 mm are considered. Since the slurry head loss data in 50 mm and 100 mm diameter pipes quite satisfactorily agree with the power law head loss model developed by IMMT, therefore, this power law model was used to compute the head loss of ash slurry in higher size pipelines.

5.2 Solids Flow rate

The solids flow rate through pipe line is given as:

$$\boxed{W_S = Q.\rho_m.C_W}$$

Where W_S is solids flow rate (tonnes/hr.)

Q = Slurry flow rate (m^3/hr.) = $\frac{\pi}{4}D^2.V.3600$

ρ_m = slurry density (tonnes/m^3)

C_W =weight concentration of solids, (fraction)

D =pipe inside diameter (m)

From the relationship mentioned above, it is obvious that, the solids flow rate would increase with increase in solids concentration, pipe diameter and slurry velocity. A slurry pipeline can record higher solids flow rates if operated at higher velocities. But it would not be technically correct, since the pipe line will incur higher power consumption and the pipe life will get drastically reduced due to high rate of erosion. Since the pipelines will operate under laminar mode at higher solids concentration, therefore the above problems can be avoided at the cost of the higher solids flow rates. By increasing the pipe diameter, the solids flow rate can increase but again the cost incurred in procuring higher sizes pipe will enhance the project cost.

5.3 Specific Power Consumption (SPC)

The Specific Power Consumption (SPC) is defined as the hydraulic power (KW) required transporting 1 tonne of material through 1 kilometer length of the pipeline. The hydraulic power required for slurry flow is calculated by the following equation:

$$P_H = \frac{QX\,\rho_m\,X\Delta H}{3.6X10^6}$$

Where, P_H =Hydraulic power (KW)

Q = Slurry flow rate (m^3/hr.)

ΔH = Head loss of slurry (m of water per km)

If W_S is the solids flow rate through the pipe line, the specific power consumption can be calculated as

$$SPC = \frac{P_H}{W_S} \quad \text{(kWH/tonne-km)}$$

Tables 46-48 presents the values of ΔH , Q , W_S , P_H and SPC for the two ash samples (Pumping Station-1 and Pumping Station-2). Considering three pipe sizes of 100 mm, 150 mm and 200 mm diameters and a slurry velocity of 2.0 m/sec. the above parameters were computed in the slurry concentration range of 50-65% by weight.

Table-46: Design parameters and specific power consumption of BPSL ash sample

Pipe diameter, m	Solids Concentration, Cw, %	Head loss, m of water/km	Slurry flow rate, m^3/hr.	Solids flow rate, tonnes/hr.	Hydraulic Power, KW/km	SPC, KWH/tonne-km
	Mixed ash slurry (Pumping Station-1)					
0.1	50	59.9	58.83	43.2	14.1	0.326
	55	68.8	58.83	49.83	16.99	0.341
	60	104.3	58.83	57.18	27.04	0.473
	62.5	179	58.83	61.14	47.72	0.78
	65	299.1	58.83	65.31	81.9	1.254
	Mixed ash slurry (Pumping Station-2)					
0.1	50	46.8	58.83	42.32	10.79	0.255
	55	46.1	58.83	48.7	11.12	0.228
	60	67.5	58.83	55.67	17.06	0.306
	62.5	128	58.83	59.41	33.158	0.558
	65	243.6	58.83	63.35	64.7	1.021

Table-47: Design parameters and specific power consumption of BPSL ash sample

Pipe diameter, m	Solids Concentration, Cw, %	Head loss, m of water/km	Slurry flow rate, m^3/hr.	Solids flow rate, tonnes/hr.	Hydraulic Power, KW/km	SPC, KWH/tonne-km
	Mixed ash slurry (Pumping Station-1)					
0.15	50	37	132.37	97.2	19.6	0.148
	55	42.6	132.37	112.14	23.67	0.211
	60	70.4	132.37	128.7	41.14	0.32
	62.5	97.2	132.37	137.6	58.3	0.424
	65	164.4	132.37	146.95	101.3	0.69
	Mixed ash slurry (Pumping Station-2)					
0.15	50	28.7	132.37	95.22	14.89	0.1564
	55	28.5	132.37	109.55	15.47	0.1412
	60	42.0	132.37	125.25	23.89	0.1907
	62.5	72.0	132.37	133.69	41.97	0.314
	65	134.9	132.37	142.54	80.614	0.5655

Table-48: Design parameters and specific power consumption of BPSL ash sample

Pipe diameter, m	Solids Concentration, Cw, %	Head loss, m of water/km	Slurry flow rate, m^3/hr.	Solids flow rate, tonnes/hr.	Hydraulic Power, KW/km	SPC, KWH/tonne-km
	Mixed ash slurry (Pumping Station-1)					
0.2	50	26.4	233.03	171.07	24.613	0.106
	55	30.6	233.03	197.415	29.93	0.1516
	60	50.1	233.03	226.505	51.54	0.2274
	62.5	63.5	233.03	242.19	63.674	0.263
	65	108.4	233.03	258.71	117.6	0.4545
	Mixed ash slurry (Pumping Station-2)					
0.2	50	20.5	233.03	167.63	18.73	0.1117
	55	20.5	233.03	192.852	19.59	0.1016
	60	30.2	233.03	220.493	30.24	0.137
	62.5	48.2	233.03	235.35	49.46	0.21
	65	89.4	233.03	250.94	94.05	0.375

5.4 Optimum transport concentration

The transport concentration of the mixed ash slurry for the two proposed pumping stations (Proposed Pumping Station-1 & 2) were optimized with respect to specific power consumption. The computed values of SPC obtained for the two ash samples at different slurry concentrations were plotted and are presented in Figures 22 and 23.

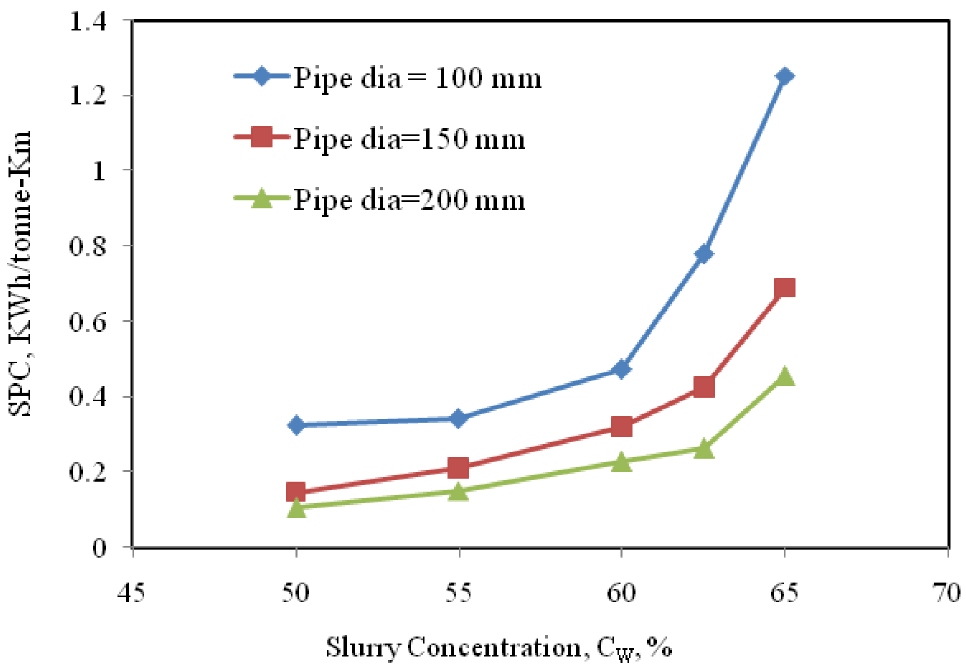

Fig. 22: SPC vs. C W of BPSL mixed ash slurry (Proposed Pumping Station-1)

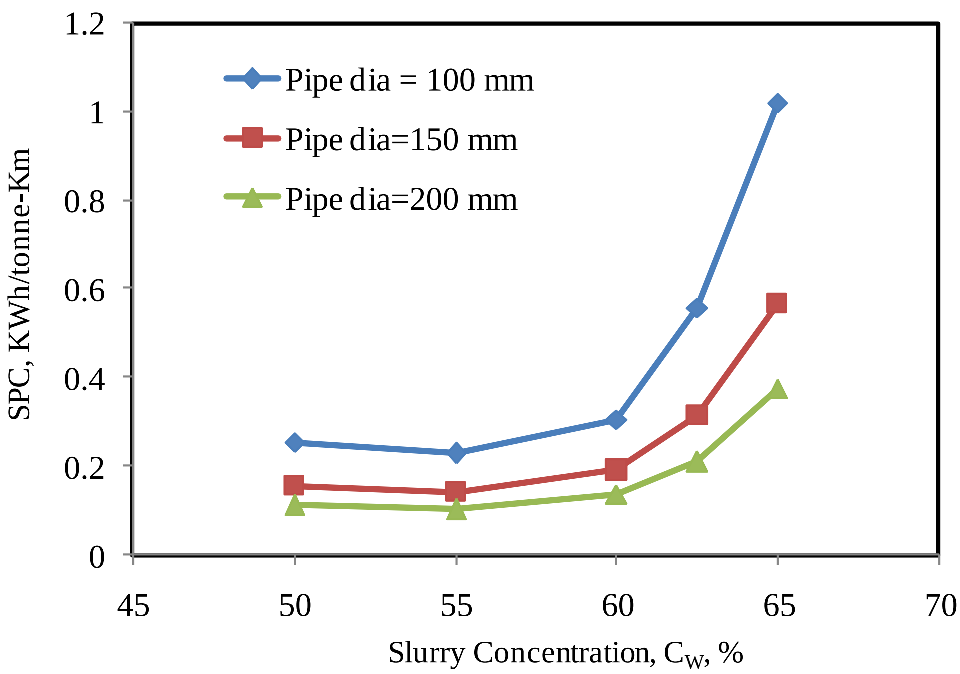

Fig. 23: SPC vs. C W of BPSL mixed ash slurry (Proposed Pumping Station-2)

It is seen from Fig. 22 that the SPC value for the Pumping Station-1 mixed ash samples increases with increase in slurry concentration for the three candidate pipes considered. The SPC value is found to be minimum at C_W=50% and the SPC value increases gradually and steadily up to a slurry concentration of 60%. Beyond a slurry concentration of 60% by weight, the SPC value sharply rises. Therefore, for hydraulic disposal of the proposed Pumping Station-1, the optimum transport concentration range of 50-60% may be considered suitable for operating the ash slurry pipelines from specific power consumption point of view.

It is further observed from Fig. 23 that the SPC value is minimum at a slurry concentration of 55% for the proposed Pumping Station-2 mixed ash samples. Beyond a slurry concentration of 60%, the SPC value increases sharply for the three candidate pipes considered. Therefore, it is recommended, to transport the mixed ash slurry for the proposed Pumping Station-2 at a slurry concentration of 55% to have substantial pipe economics.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The characterization, rheological and pipe loop tests conducted on BPSL ash samples indicated the following.

- The chemical analysis of the mixed ash samples for the two proposed Pumping Stations indicated that the alumina and silica contents of the mixed ash samples of Pumping Station-2 is higher than that of Pumping Station-1. The alumina and silica contents of Pumping Station-1 are 20.65% and 52.25% respectively. Similarly, the alumina and silica contents of Pumping Station-2 are 28.87% and 59.5% respectively.

- The particle size distribution of the ash samples procured from various sources of generation indicated that the ash samples of AFBC boilers are comparatively coarser in nature than those of CFBC boilers. The ESP ash samples of both AFBC and CFBC boilers, WHRB ash samples and de-dusting ash samples are relatively finer in nature and the median particle sizes (d_{50}) of these ash samples were found to be in the range of 12- 28 **µ**m. The d_{50} of Economizer ash samples from CFBC and AFBC boilers were determined to be 57.3 **µ**m and 225.8 **µ**m respectively. The particle sizes of the bed ash generated in both the cases are quite large. The median particle size (d_{50}) of CFBC bed ash and AFBC bed ash samples were found to be 290 **µ**m and 450 **µ**m respectively. The particle size of air pre-heater ash samples generated in AFBC boilers was also quite large and the d_{50} of this APH ash was found to be 308 µm.

- The particle size distribution of the mixed ash samples for the proposed two HCSD pumping stations indicated that the mixed ash samples of Pumping Station-1 is relatively finer than that of Pumping Station-2.

- The ash samples of the Proposed Pumping Station-2 were found to be acidic in nature while the ash samples of the Proposed Pumping Station-1 were found to be alkaline in nature.

- It was observed from the maximum static settled concentration tests (sedimentation tests) that the mixed ash slurry at the proposed Pumping Station-2 can be transported at higher solids concentration than that of Pumping Station-1. The $C_{W\text{-}max}$ value achieved by the mixed ash samples of Pumping Station-1 and 2 were found to be 68.18% and 68.8% respectively.

- The rheological studies conducted on the ash samples in the slurry concentration range of 50-65% by weight quite reasonably fitted to power law model. The viscosity ash slurry increased with increase in slurry concentration.

- The pipe loop tests conducted in 50 mm and 100 mm dia pipe using the high concentration slurry test loop facility at IMMT indicated that mixed ash slurry samples of the proposed HCSD Pumping Station-1 incurred higher head loss/pressure drop than that of Pumping Station-2 in the studied concentration range of 50-65% by weight.

- The Specific Power Consumption (SPC) values evaluated for three candidate pipe sizes 100 mm , 150 mm and 200 mm indicated that the SPC values were quite high for operating the pipe lines beyond a slurry concentration of 60% by weight (Pumping Station 1 and 2). The computed values of SPC for the proposed Pumping Station-1 mixed ash samples indicated higher values than that of Pumping Station-2.

- Therefore, it is recommended that the proposed HCSD system at Pumping Station-1 may be operated in the slurry concentration range of 50-55% while the Pumping Station-2 may be operated at a slurry concentration of 55% by weight to have substantial pipe economics from specific power consumption point of view.

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